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New Measurement of Parity Violation in Elastic Electron-Proton Scattering and Implications for Strange Form Factors

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Abstract

We have measured the parity-violating electroweak asymmetry in the elastic scattering of polarized electrons from the proton. The result is $A = -15.05 \pm 0.98(stat) \pm 0.56(syst)$ ppm at the kinematic point $\langle\theta_{lab}\rangle = 12.3^\circ$ and $\langle Q^2 \rangle = 0.477$ (GeV/c)². Both errors are a factor of two smaller than those of the result reported previously. The value for the strange form factor extracted from the data is $(G_E^s + 0.392G_M^s) = 0.025 \pm 0.020 \pm 0.014$, where the first error is experimental and the second arises from the uncertainties in electromagnetic form factors. This measurement is the first fixed-target parity violation experiment that used either a “strained” GaAs photocathode to produce highly polarized electrons or a Compton polarimeter to continuously monitor the electron beam polarization.

Key words:

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It is well known that strange quarks and antiquarks are present in the nucleon. An important open question is the role that sea (non-valence) quarks in general and strange quarks in particular [1] play in the fundamental properties of the nucleon. For example, do strange quarks contribute to the charge radius or magnetic moment of the proton? If so, the strange form factors G_E^s and G_M^s are relevant. A number of papers have suggested that indeed these form factors may be large [1–10]. Others models suggest small contributions [11–14].

Strange form factors can be isolated from up and down quark form factors by measuring the parity-violating asymmetry $A = (\sigma_R - \sigma_L)/(\sigma_R + \sigma_L)$ in the elastic scattering of polarized electrons from protons [15,16]. The experiments are challenging since $A \approx A_0\tau \approx 10$ parts per million (ppm). Here $A_0 = (G_F M_p^2)/(\sqrt{2}\pi\alpha) = 316.7$ ppm, where G_F is the Fermi constant for muon decay and M_p is the proton mass. Also $\tau = Q^2/4M_p^2$ where Q^2 is the square of the four-momentum transfer. Nevertheless, several experiments have recently published results for A [17–19]. In this letter, we present the most precise measurement to date for A of the proton and determine new limits for the possible contribution of strange form factors.

Measurements of elastic electromagnetic and electroweak nucleon scattering provide three sets of vector form factors. From this information, the form factors for each flavor may be determined [20]: $G_{E,M}^u$, $G_{E,M}^d$, and $G_{E,M}^s$. A convenient alternate set, which is directly accessible in experimental measurements, is the electromagnetic form factors $G_{E,M}^{p\gamma}$, $G_{E,M}^{n\gamma}$, plus $G_{E,M}^0$. Here

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$G^0 = (G^u + G^d + G^s)/3$, $G^{p\gamma} = \frac{2}{3}G^u - \frac{1}{3}G^d - \frac{1}{3}G^s$, and $G^{n\gamma} = \frac{2}{3}G^d - \frac{1}{3}G^u - \frac{1}{3}G^s$, where the last expression assumes charge symmetry. G^0 cannot be accessed in electromagnetic scattering and thus represents new information on nucleon dynamics that can be accessed only via measurements of the weak neutral current amplitude.

The theoretical asymmetry in the Standard Model has a convenient form in terms of G^0 :

$$A_{th} = -A_0\tau\rho'_{eq}\left(2 - 4\hat{\kappa}'_{eq}\sin^2\theta_W - \frac{\varepsilon\eta_p}{\varepsilon\eta_p^2 + \tau\mu_p^2}\frac{G_E^0 + \beta G_M^0}{(G_M^p/\mu_p)}\right) - A_A \quad (1)$$

where $\mu_p(\mu_n) \approx 2.79(-1.91)$ is the proton(neutron) magnetic moment in nuclear magnetons, $\eta_p = \eta_p(Q^2) = G_E^{p\gamma}(Q^2)/(G_M^{p\gamma}(Q^2)/\mu_p)$, $\varepsilon = (1 + 2(1 + \tau)\tan^2\theta/2)^{-1}$ is the longitudinal photon polarization, and $\beta = \tau\mu_p/(\varepsilon\eta_p)$. The scattering angle of the electron in the laboratory is θ . The contribution from the proton axial form factor, $A_A = (0.56 \pm 0.23)$ ppm, is calculated to be small for our kinematics [21,22]. The recent datum from the SAMPLE collaboration [23] is 1.5 standard deviations larger than the prediction. [21,22]

The parameters $\rho'_{eq} = 0.9879$ and $\hat{\kappa}'_{eq} = 1.0029$ include the effect of electroweak radiative corrections [24], and $\sin^2\theta_W = 0.2314$. If, in addition to $G_{E,M}^0$, the proton and neutron electromagnetic form factors $G_{E,M}^{p\gamma}$ and $G_{E,M}^{n\gamma}$ are known, the strange form factors may be determined from

$$G_{E,M}^s = G_{E,M}^0 - G_{E,M}^{p\gamma} - G_{E,M}^{n\gamma}. \quad (2)$$

This experiment took place in Hall A at the Thomas Jefferson National Accelerator Facility. An approximately $35\mu\text{A}$ beam of 67-76% polarized electrons with an energy of 3.3 GeV scattered from a 15 cm liquid hydrogen target. Elastic events were detected by integrating the signal in total-absorption counters located at the focal plane of a pair of high-resolution magnetic spectrometers. [18,25]

It is important that the signal be purely elastic, since background processes may have large asymmetries. For example, the production of the prominent Δ -resonance is calculated to have 3 times the asymmetry of elastic scattering. [20] To measure the rejection of unwanted events by our system, we measured the response of the detector, both in counting and integrating mode, as a function of the mismatch between the spectrometer setting and the momentum of elastic events. The result, shown in Fig. 1, is that the integrated response drops many orders of magnitude as the momentum mismatch increases. Based on these data, we determined that only 0.2% of our signal arises from inelastic background processes. Quasi-elastic scattering from the

Al target windows contributed 1.5% to the measured signal. The net effect of all the backgrounds is listed in Table 1.

A new feature of the experiment is that the beam polarization $P_e \approx 70\%$. This was achieved by using photoemission by circularly polarized laser light impinging on a “strained” GaAs crystal. A plot of the polarization versus time for part of the run is given in Fig. 2. The starred points are from Møller scattering and the dots are preliminary data from the recently commissioned Compton polarimeter. The errors in the Møller data have been reduced by a factor of two from those of Ref. [18] by improving our knowledge of the polarization of the electrons in the magnetized foil target and our understanding of rate effects in the Møller spectrometer. The Compton device continuously monitored the polarization of the beam on target and ruled out possible significant variations in polarizations between the daily Møller measurements. Both devices have an overall systematic error $\Delta P_e/P_e \sim 3.2\%$.

To study possible systematic errors in our small asymmetry, we sometimes inserted a second half-wave ($\lambda/2$) plate in the laser beam at the source to reverse the sign of the helicity. Data were obtained in sets of 24-48 hour duration, and the state of the $\lambda/2$ plate was reversed for each set. The resulting asymmetries are shown in Fig. 3a. The asymmetry reverses as expected but otherwise behaves statistically.

The strained GaAs crystal, in contrast to the bulk GaAs used for our previous work [18], has a large analyzing power for linearly polarized light. [26] The consequence was a tendency for much larger helicity-correlated differences in the beam position. We found that an additional half-wave plate in the laser beam reduced this problem to a manageable level. In addition, the intensity asymmetry of the beam in another experiential hall was nulled to prevent beam loading in the accelerator from inducing position correlations in our beam. The remaining position and energy differences were measured with precision microwave monitors. One example of monitor data is shown in Fig. 3b. The effect of these beam differences on the asymmetry was measured by calibrating the apparatus with beam correction coils and an energy vernier. The resultant correction, shown in Fig. 3c, proved to have an average of 0.02 ± 0.02 ppm.

The experimental asymmetry, corrected for the measured beam polarization, is $A_{exp} = -15.1$ at $Q^2 = 0.477$ (GeV/c)² for the 1999 data. We also include the previously reported 1998 data, [18] which gives $A_{exp} = -14.7$ ppm when extrapolated to the same Q^2 value but with approximately twice the statistical and systematic errors. In addition, three small corrections based on subsequent data analysis were made to the 1998 data: i) the background correction was included; ii) the measured beam polarization was reduced by 1.5%; and iii) the Q^2 value was determined to be 0.474 (GeV/c)² instead of 0.479 (GeV/c)². An increase of 1% in Q^2 is expected to increase the magnitude of the asymmetry

by 1.5%. The errors for the full data set are given in Table 1. Systematic errors in the beam polarimetry and in the measurement of the spectrometer angle were the most significant sources. The combined result is $A_{exp} = 15.05 \pm 0.98(stat) \pm 0.56(syst)$ ppm at the average kinematics $Q^2=0.477$ (GeV/c)² and $\theta = 12.3^\circ$. This is the average asymmetry over the finite solid angle of the spectrometers; we estimate the value at the center of acceptance is smaller by 0.7%.

By using Eq. 1 and the theoretical value for A_A [21,22], we obtain $(G_E^0 + \beta G_M^0)/(G_M^{p\gamma}/\mu_p) = 1.527 \pm 0.048 \pm 0.027 \pm 0.011$. Here the first error is statistical, the second systematic, and the last error is due to the uncertainty from A_A . For our kinematics $\beta = 0.392$. The sensitivity to η_p is negligible. To determine the contribution due to strange form factors, we use Eq. 2 and data for the electromagnetic form factors. The values we use [27–34] are summarized in Table 2. Thus we have $G_E^s + \beta G_M^s = 0.025 \pm 0.020 \pm 0.014$, where the first error is the errors in G^0 combined in quadrature and the second due to the electromagnetic form factors. This value is consistent with the hypothesis that the strange form factors are negligible.

We note that there are data for G_M^n [35] that are less precise but at variance with those of Ref. [29]. Our result for $G_E^s + \beta G_M^s$ would increase by 0.020 if the data from Ref. [35] were used. New data for both G_M^n and G_E^n are in the early stages of analysis and will be important both for validating our choices and also for interpreting future data on strange form factors.

In Fig. 4, we plot the above value for $G_E^s + \beta G_M^s$ as a band with the errors added in quadrature. The dots represent the predictions from those models that apply at our value of Q^2 . Our result restricts significantly the possible “parameter space” for strangeness to be an important degree of freedom in nucleon form factors. However, our data are compatible with several models that predict large strange form factors, including two with $G_E^s \approx -0.39 G_M^s$, [8,9] and one where the prediction happens to cross zero near our Q^2 value.[5]

Our collaboration has two new experiments approved at JLab for a kinematic point at $Q^2 \sim 0.1$ (GeV/c)². One, using a hydrogen target, will measure the same combination of strange form factors at a low Q^2 [36] and the other, using a ⁴He target, will be sensitive to G_E^s but not G_M^s . [37] Thus these experiments might detect the presence of strange form factors that cannot be excluded by the present result.

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Table 1

Summary of corrections and contributions to the errors in % for the measured asymmetry.

Source	Correction (%)	$\delta A/A(\%):1998$	$\delta A/A(\%):1999$
Statistics	—	13.3	7.2
P_e	—	7.0	3.2
Q^2	—	1.8	1.8
Backgrounds	1.2	0.6	0.6

Table 2

Electromagnetic form factors normalized to G_M^p/μ_p . The last column is the error in A_{th} from the quoted error in the corresponding form factor.

Form Factor	Value	Ref.	$\delta A_{th}/A_{th}$
$G_E^p/(G_M^p/\mu_p)$	0.99 ± 0.02	[27,28]	3%
$G_E^n/(G_M^p/\mu_p)$	0.16 ± 0.03	[30–34]	4%
$(G_M^n/\mu_n)/(G_M^p/\mu_p)$	1.05 ± 0.02	[29]	2%

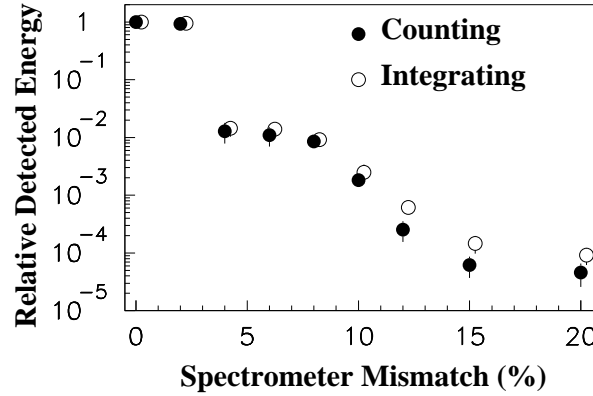


Fig. 1. Fraction of energy deposited in the detector as a function of spectrometer mismatch. The inelastic threshold corresponds to a mismatch of about 4.5%, where the response of the detector is already reduced by a factor of 100.

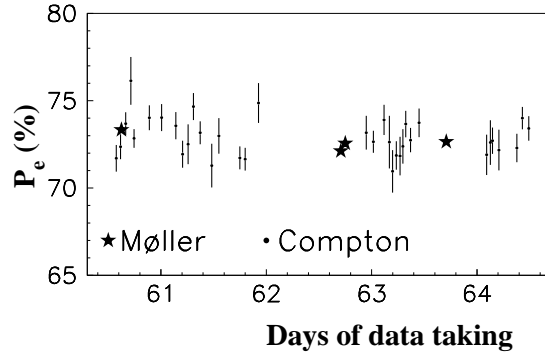


Fig. 2. Electron beam polarization for part of the run. The statistical errors on the Møller data are smaller than the points.

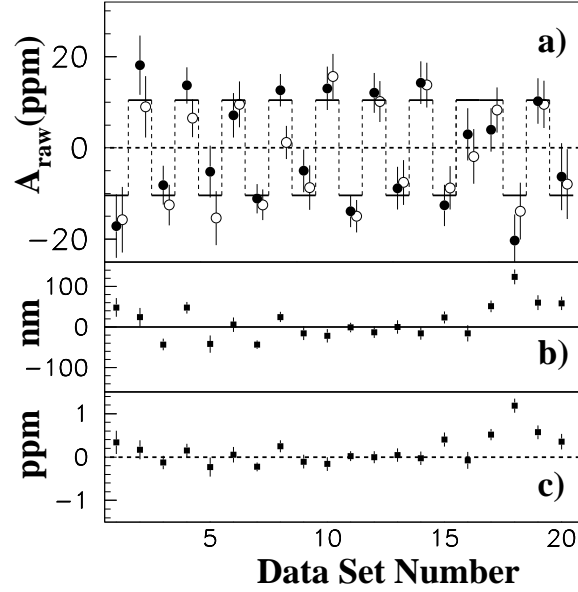


Fig. 3. a) Raw asymmetry versus data set. Solid(open) circles are from the left(right) spectrometer. The step pattern is due to the insertion of the half-wave plate. The $\chi^2 = 33.7$ for 39 degrees of freedom. b) Helicity-correlated horizontal position difference measured near the target. c) Correction to left spectrometer data due to all of the beam parameter differences. The corrections for the right spectrometer are smaller.

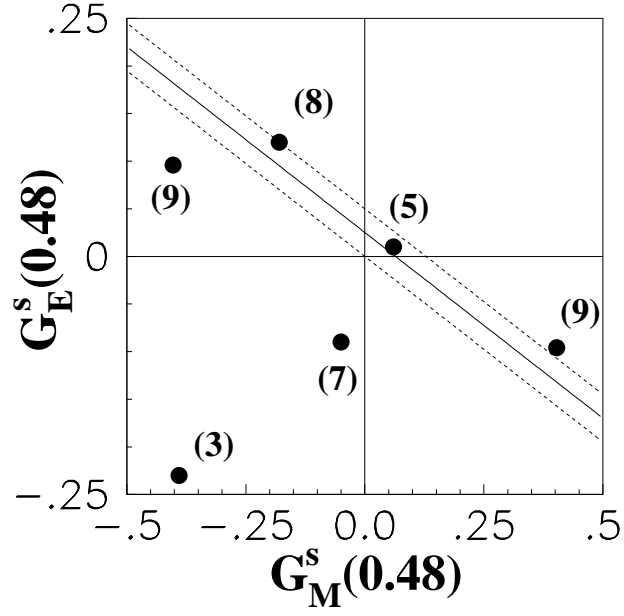


Fig. 4. Plot of G_E^s versus G_M^s at $Q^2 = 0.477 \text{ (GeV/c)}^2$. The band is the allowed region derived from our results. The width of the band is computed by adding the errors in quadrature. The points are various estimates from models that make predictions at our value of Q^2 . The numbers in the brackets are the reference of the models. Ref. [9] is plotted twice due to an ambiguity in the predicted sign.